Experimental aspects of jet physics in ep collisions

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Introduction

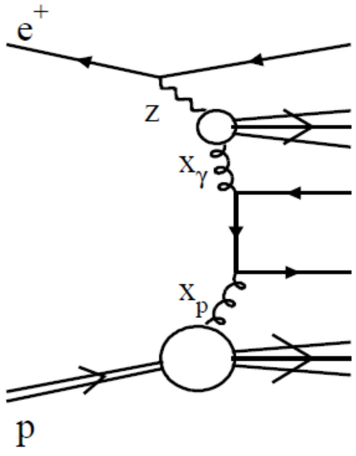
- Basics of jet finding in ep
- Example application: Accessing gluons with di-jets
- Limits of jet applicability: How low in transverse momentum can we go?

Simulation Details / Particle Cuts

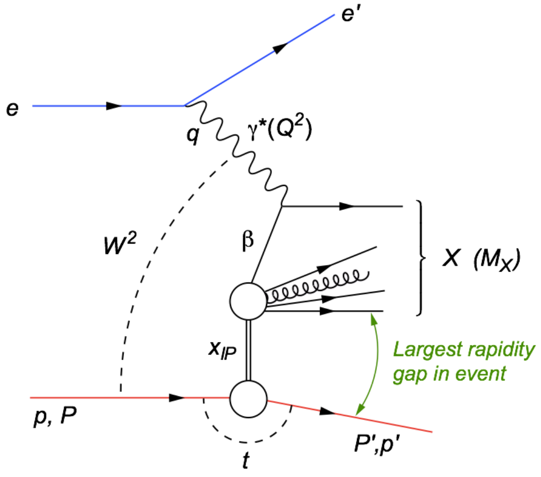
- Electron – Proton events generated using PYTHIA
- Full energy eRHIC: 20 x 250 GeV ($\sqrt{s}$ = 141 GeV)
- Cut on inelasticity: $0.01 \leq y \leq 0.95$
- Particles used in jet finding:
  - Stable
  - $p_T \geq 250$ MeV
  - $\eta \leq 4.5$
  - Parent cannot originate from scattered electron

Subprocesses

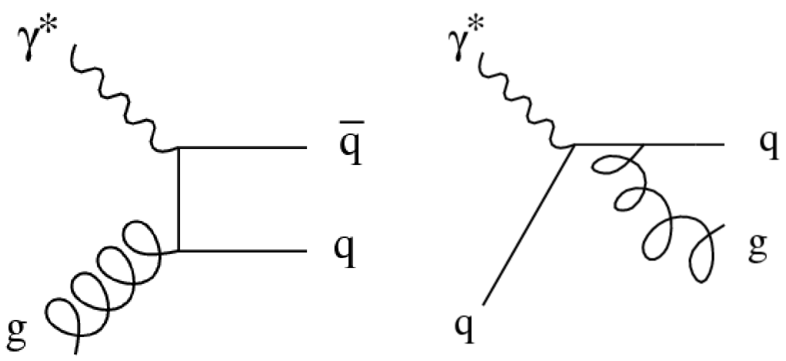
Resolved



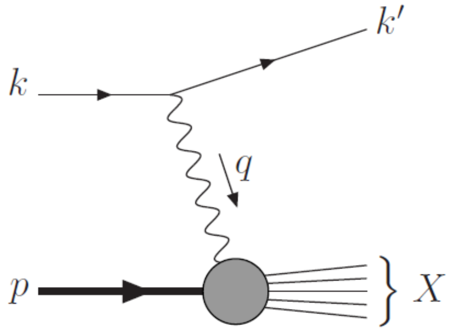
Diffractive



Photon-Gluon Fusion & QCD-Compton

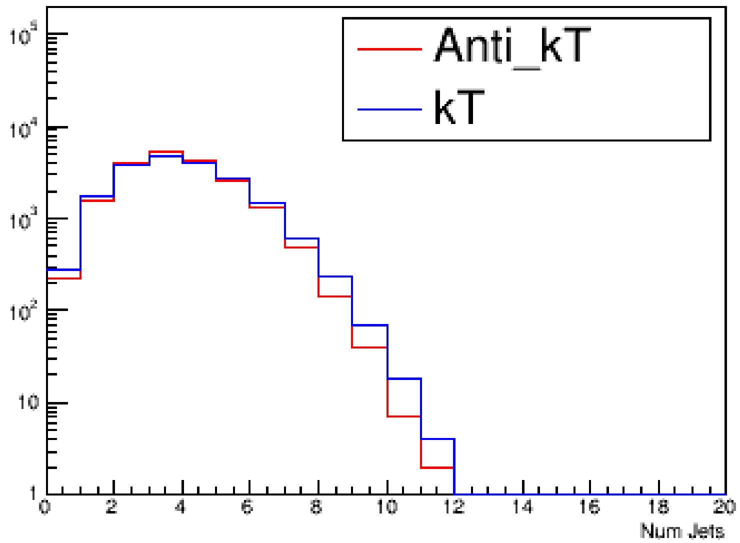


DIS



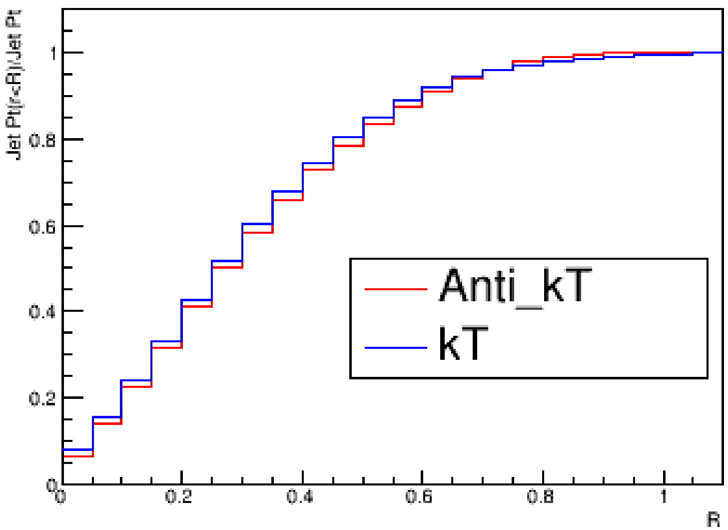
Jet Basics: Algorithm

Number of Jets



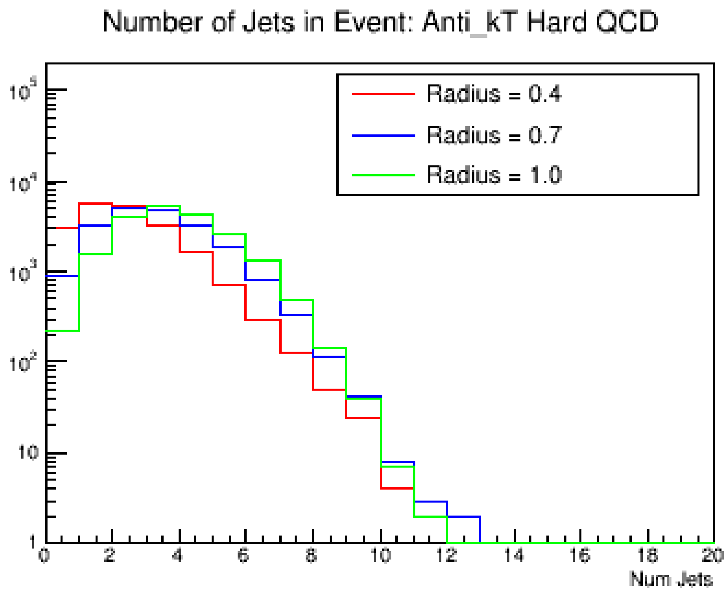
- Many jet clustering algorithms available
- Compare k_T and anti-k_T (widely used at hadron colliders)
- Infrared and collinear safe at all orders

Jet Profile



- Parameters: Radius = 1, Min p_T = 1.0 GeV, Resolved Processes
- Look at number of jets in event and jet profile (amount of jet p_T in certain radius)
- k_T and anti-k_T show very similar behavior

Jet Basics: Radius

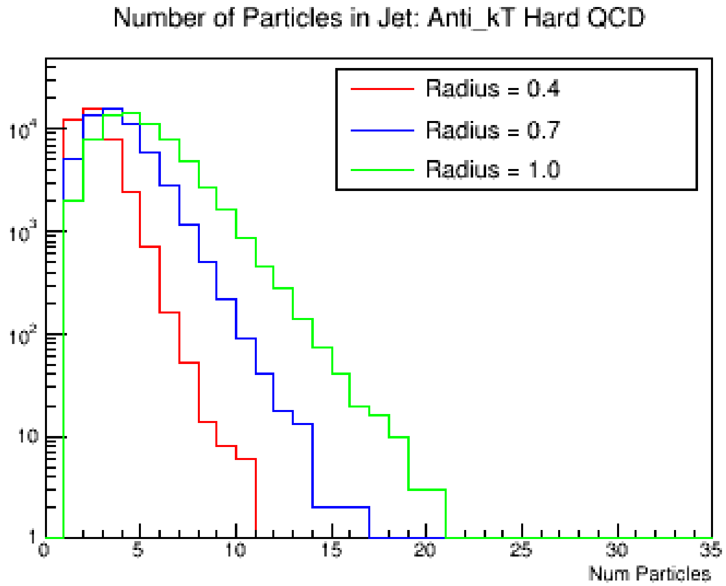


- For anti-k_T algorithm the radius parameter determines the distance at which particles can be grouped together

- Sets the effective size of the jet

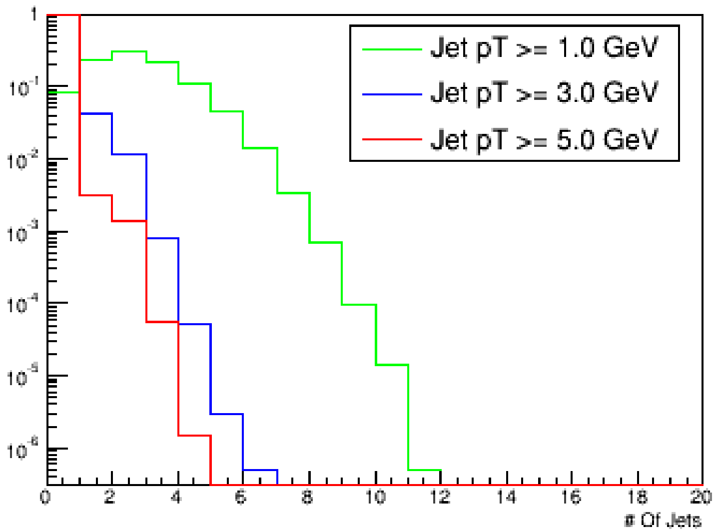
- Parameters: Min p_T = 1.0 GeV, Resolved processes

- Larger radii result in more found jets as well as more particles in jet

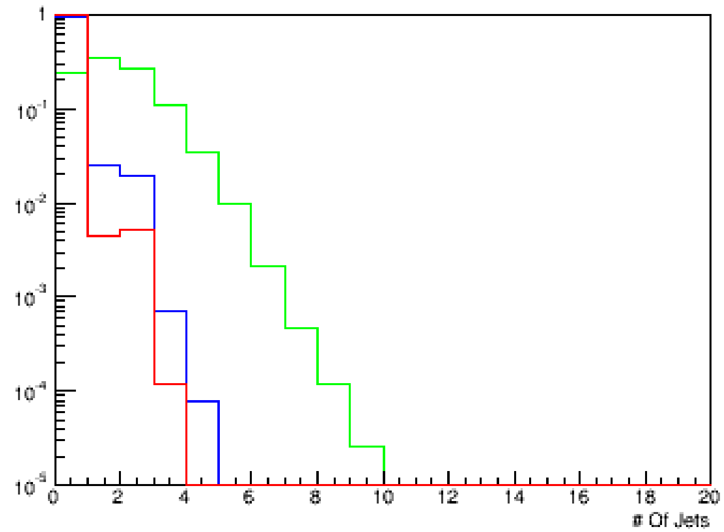


Jet Multiplicity: $Q^2 = 0.01 – 0.1\ GeV^2$

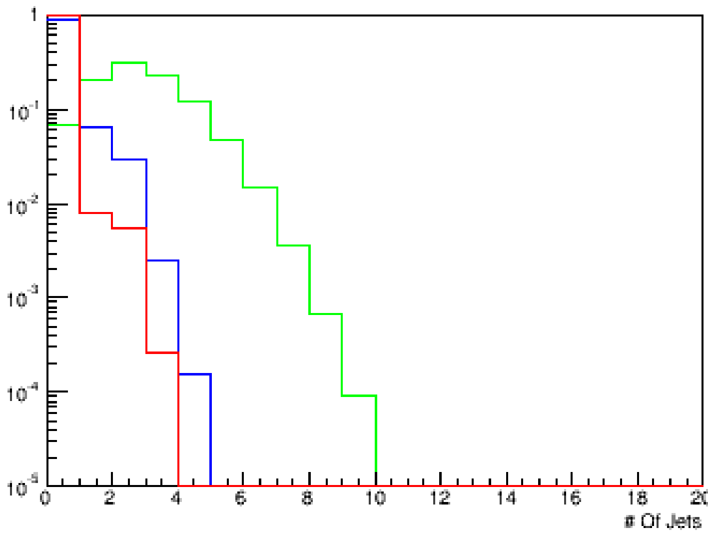
Jets: Resolved Processes



Jets: QCDC



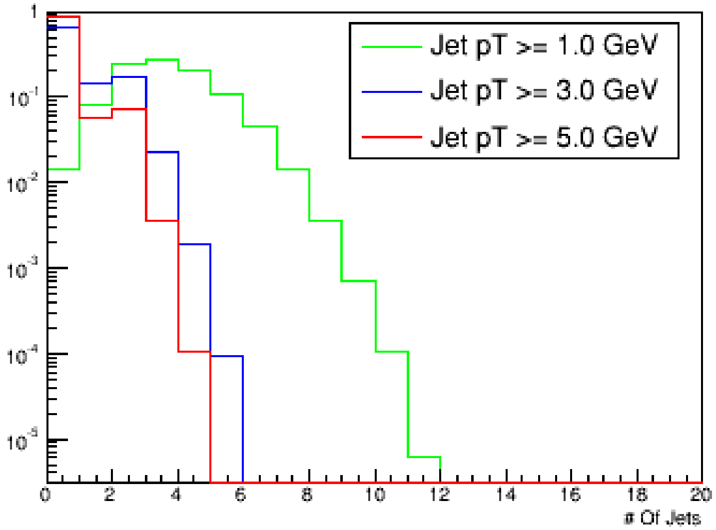
Jets: PGF



- Percentage of events with a certain number of found jets for different minimum allowed jet p_Ts
- See a decrease in number of jets with increasing minimum jet p_T
- Jet p_T of 1 GeV may not be well described theoretically
- Each curve normalized to unity

Jet Multiplicity: Q^2 = 10 – 100 GeV^2

Jets: Resolved Processes



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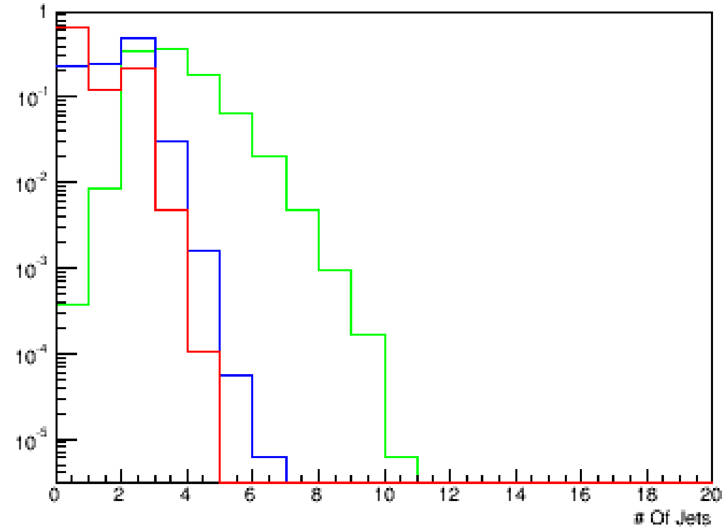
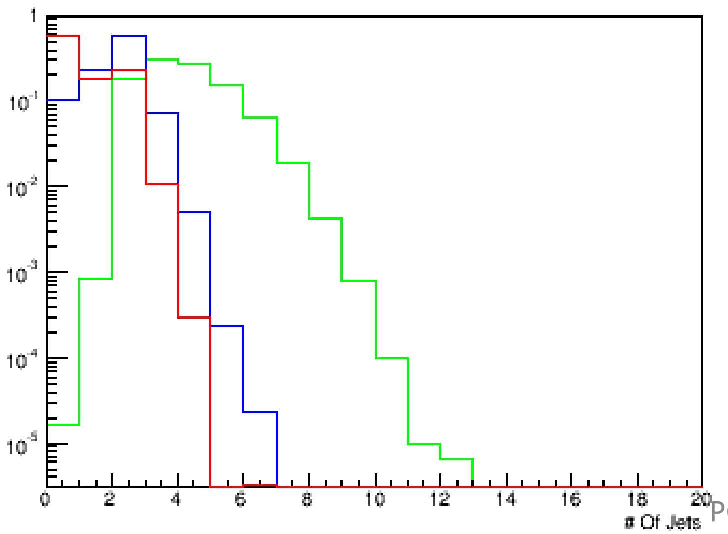
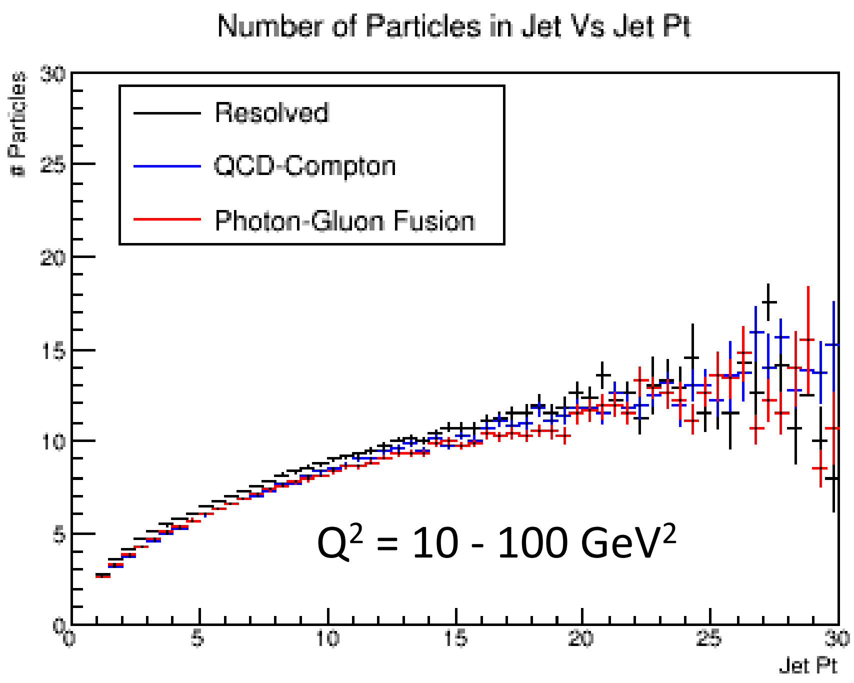


Jets: PGF

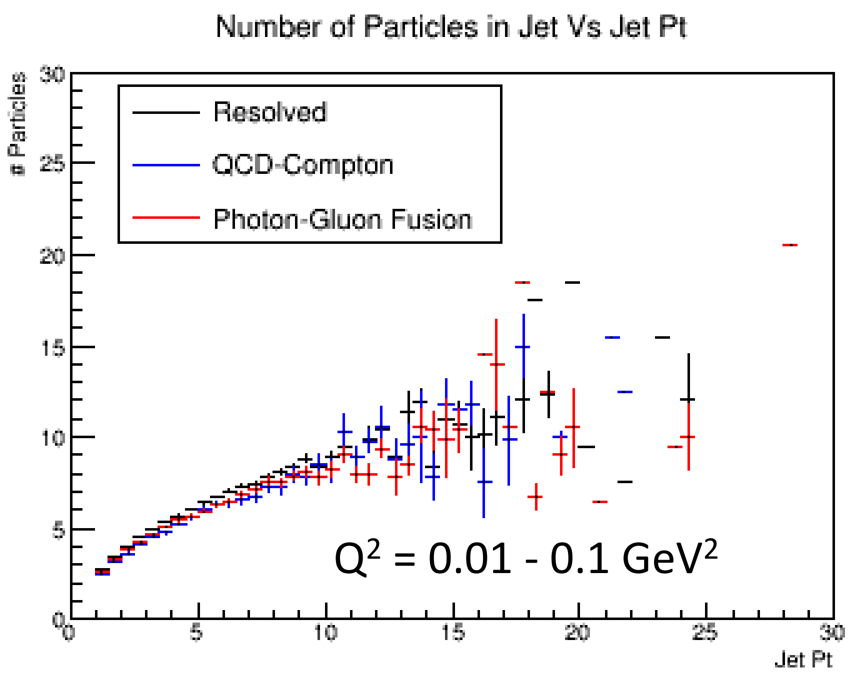


- Same as above for higher Q^2 range
- Note the increase in percentage of events containing jets

Jet Particle Multiplicity



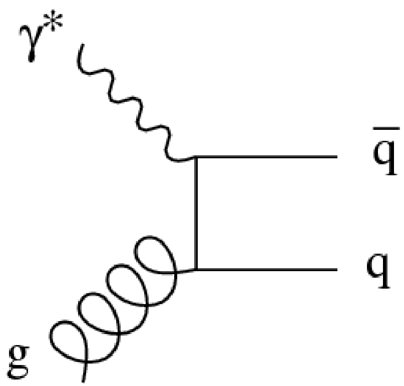
- Look at the average number of particles in jet as a function of jet p_T
- All stable particles (charged and neutral) are counted



- No dependence on Q2 or subprocess
- How few particles can be in jet before it doesn't make sense to call the object a jet?

Accessing Gluons with Di-jets

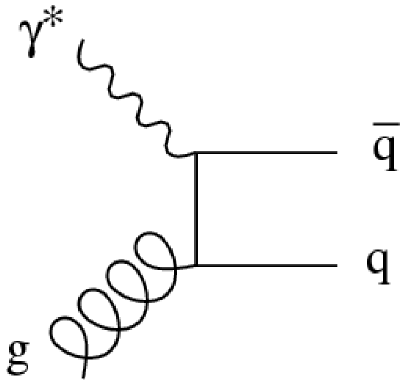
Photon-Gluon Fusion



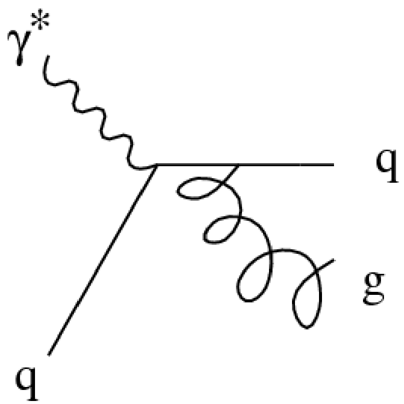
- Gluons can be probed in DIS via the higher-order photon gluon fusion process

Accessing Gluons with Di-jets

Photon-Gluon Fusion

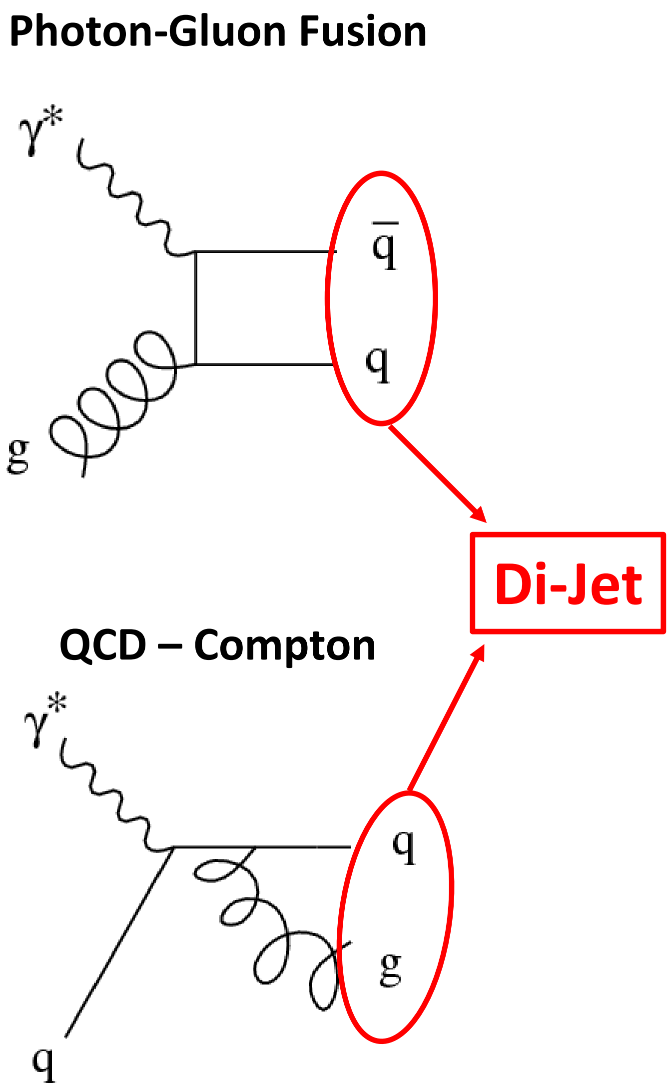


QCD – Compton



- Gluons can be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order

Accessing Gluons with Di-jets



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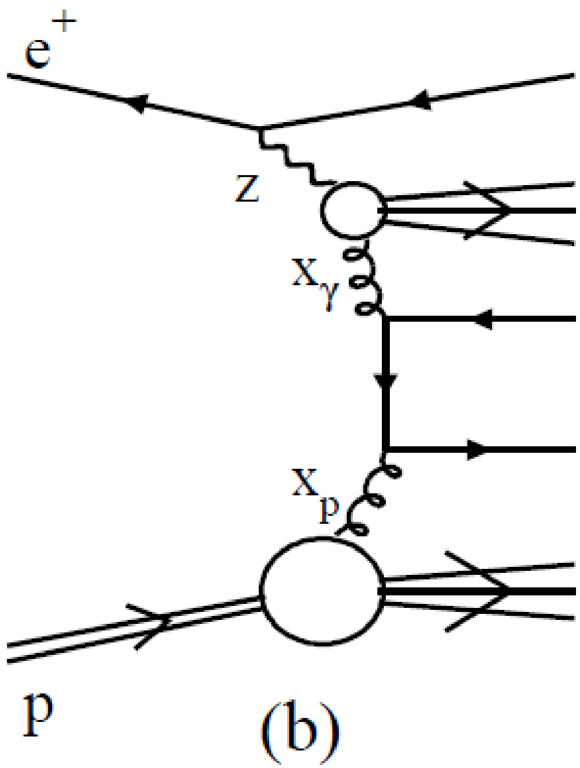
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet

Accessing Gluons with Di-jets

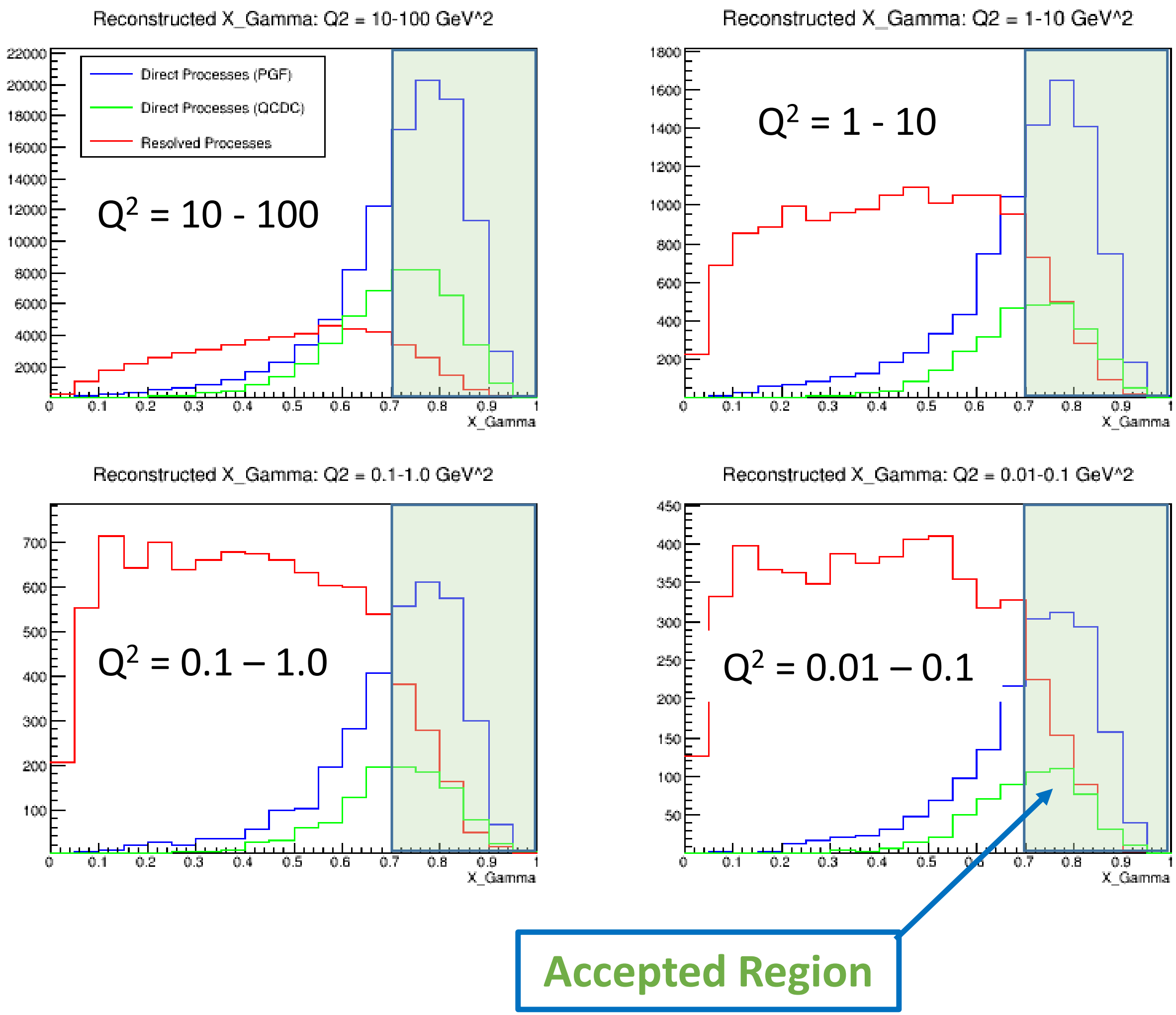
Resolved



- Gluons can be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet
- At lower Q^2, resolved processes in which the photon assumes a hadronic structure begin to dominate
- Interested in the parton from the proton, would like to suppress the resolved component

Direct Vs Resolved Processes

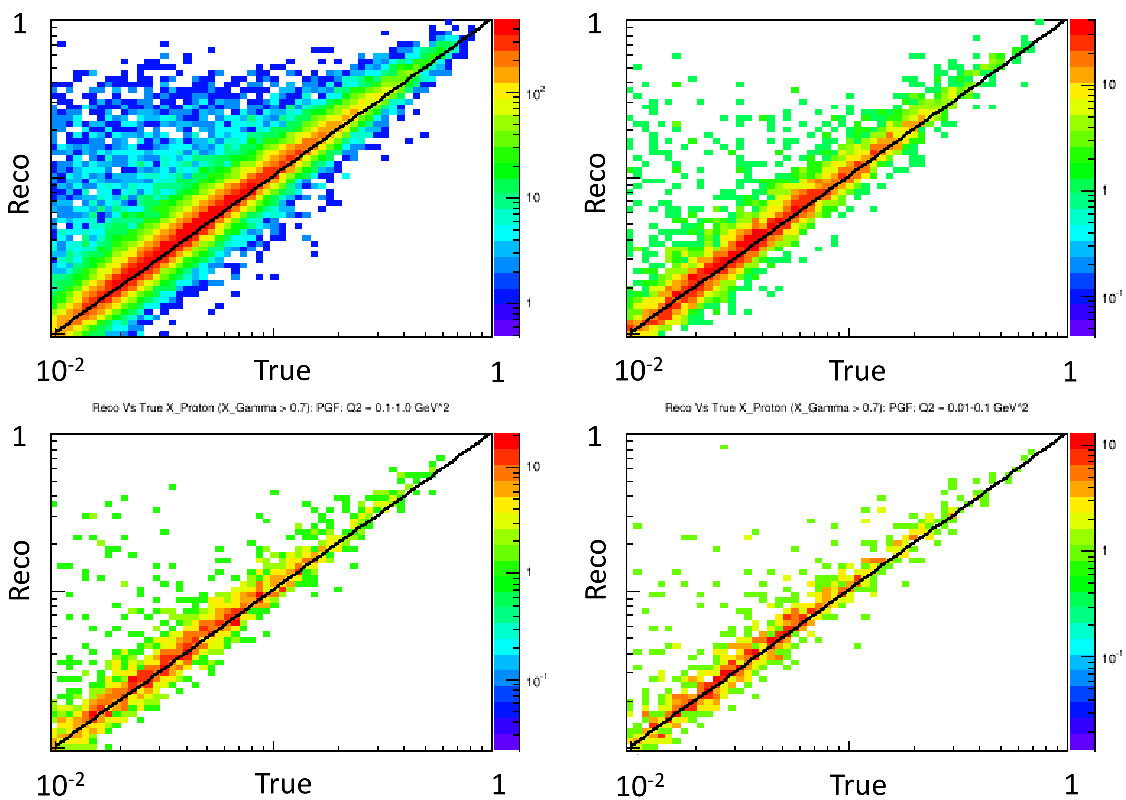
$$X_\gamma = \frac{1}{2E_e y}\left(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}\right)$$



- Plot reconstructed X_γ for direct and resolved processes
- Direct processes should concentrate toward 1 while resolved processes are at lower values
- Direct processes dominate at higher Q^2 while resolved are more prevalent at low Q^2
- Cut of $X_\gamma > 0.7$ enhances the direct fraction at all Q^2

Proton Partonic Kinematics

Parton Momentum Fraction: Photon Gluon Fusion



- To measure gluon, need to probe the parton coming from the proton
- Momentum fraction of the parton from proton is well reconstructed

$$X_{q,g} = \frac{1}{2E_P}\left(p_{T1}e^{\eta_1} + p_{T2}e^{\eta_2}\right)$$

Proton Partonic Kinematics

$$X_{q,g} = x_B\left(1 + \frac{M^2}{Q^2}\right)$$

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- $X_{q,g}$ is related to Bjorken-x and Q^2 at leading order

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$$Q^2 = syx_B$$

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- Q^2 and Bjorken-x are also related via the collision energy and inelasticity

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- Accessible $X_{q,g}$ range basically determined by beam energies

Proton Partonic Kinematics

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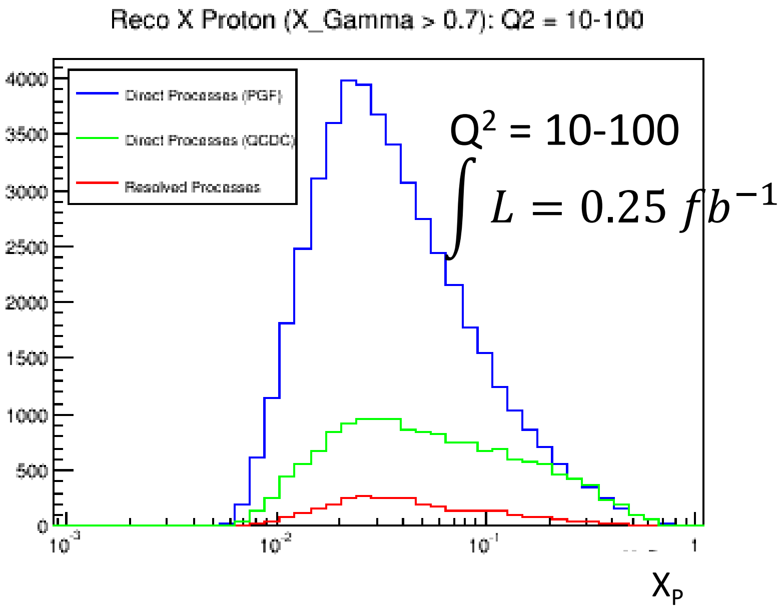
$$Q^2 = syx_B$$

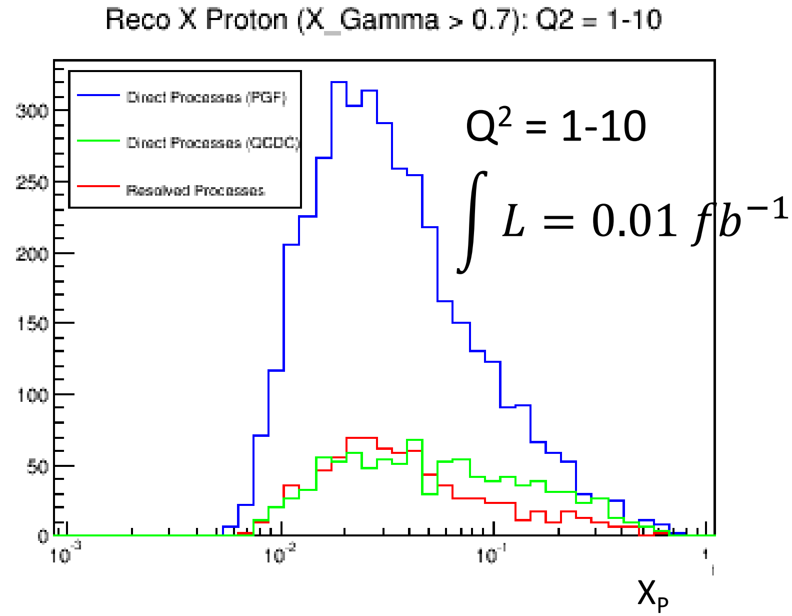
$$X_{q,g} = x_B + \frac{M^2}{sy}$$

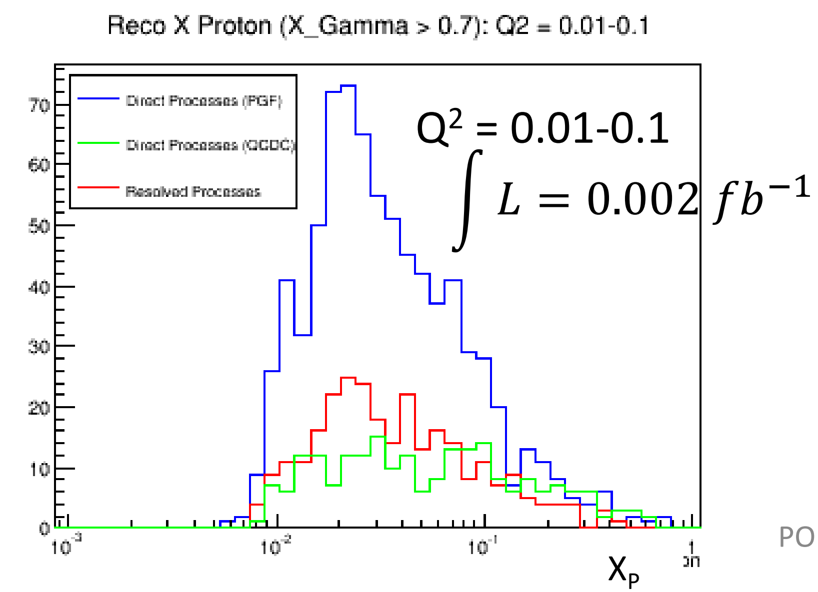
$$\boxed{\approx \frac{100}{(20000\ x\ 0.95)} \approx 0.005}$$

- To measure gluon, need to probe the parton coming from the proton
- Momentum fraction of the parton from proton is well reconstructed
- $X_{q,g}$ is related to Bjorken-x and Q^2 at leading order
- Q^2 and Bjorken-x are also related via the collision energy and inelasticity
- Accessible $X_{q,g}$ range basically determined by beam energies
- Lowest $X_{q,g}$ we can probe is about 0.005

$X_{q,g}$ For Different Q^2







- At lower Q^2, contribution from resolved process increases while QCD Compton contribution decreases
- For a given di-jet mass range, same $X_{q,g}$ can be probed over large range of Q^2
- Can test evolution of gluons

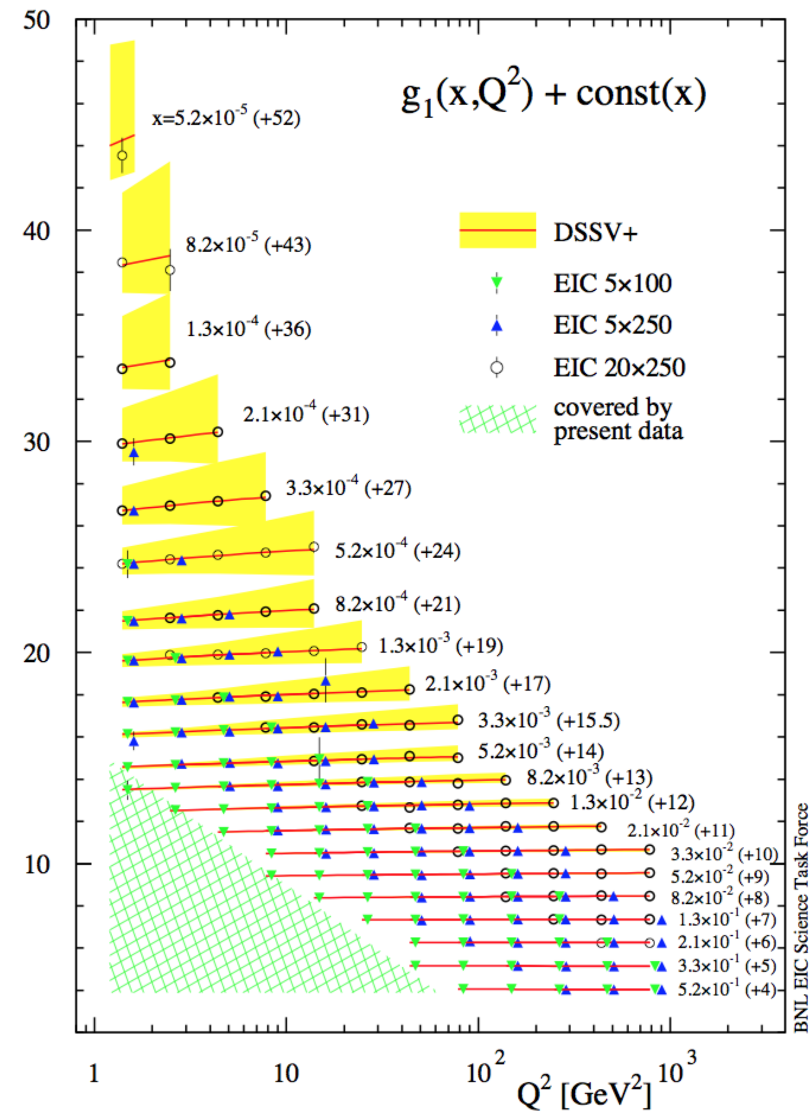
Accessing ΔG

- Several observables are sensitive to ΔG in DIS but golden measurement at an EIC would be scaling violation of $g_1(x,Q^2)$

$$\frac{dg_1(x,Q^2)}{dln(Q^2)} \approx -\Delta g(x,Q^2)$$

- Current DIS constraints on ΔG hampered by limited x & Q^2 coverage

- EIC would greatly expand kinematic reach and precision of $g_1(x,Q^2)$ measurements!



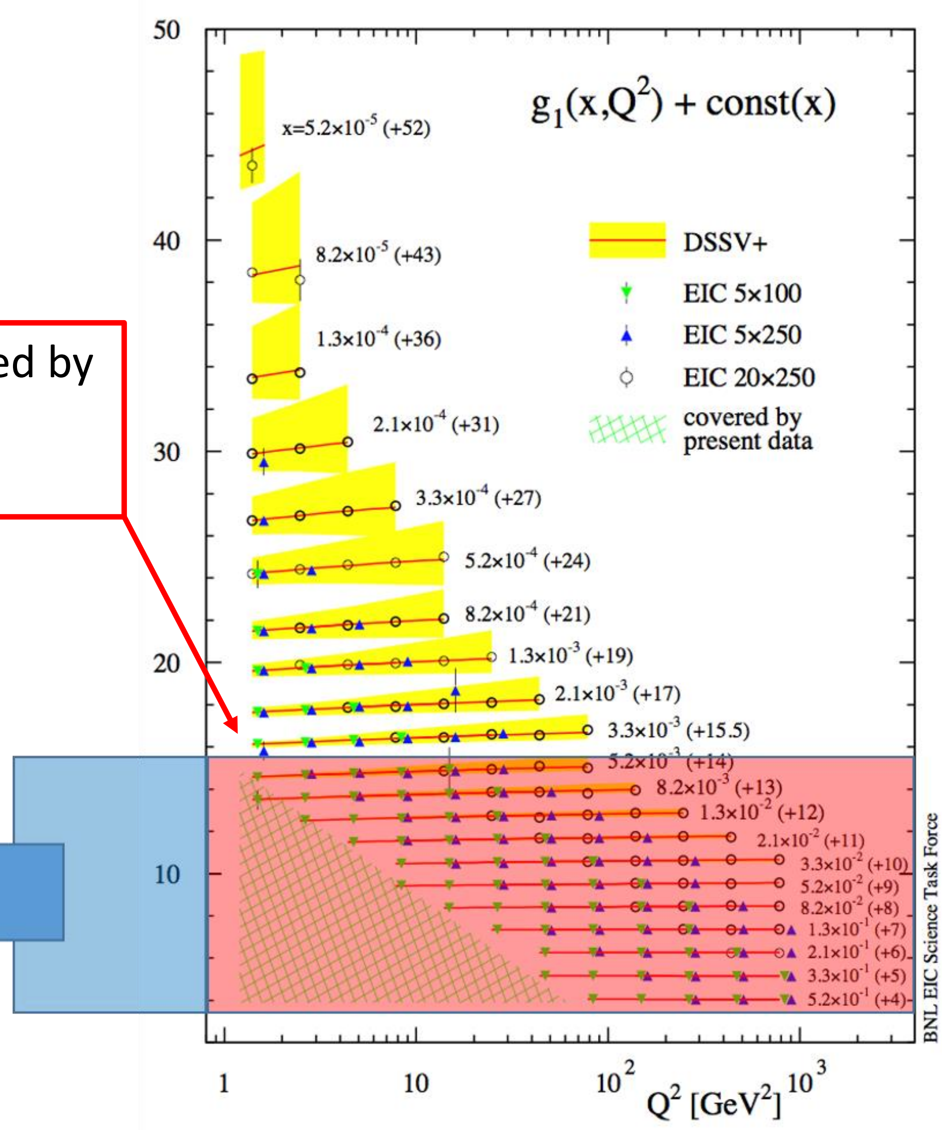
arXiv:1206.6014

Accessing ΔG

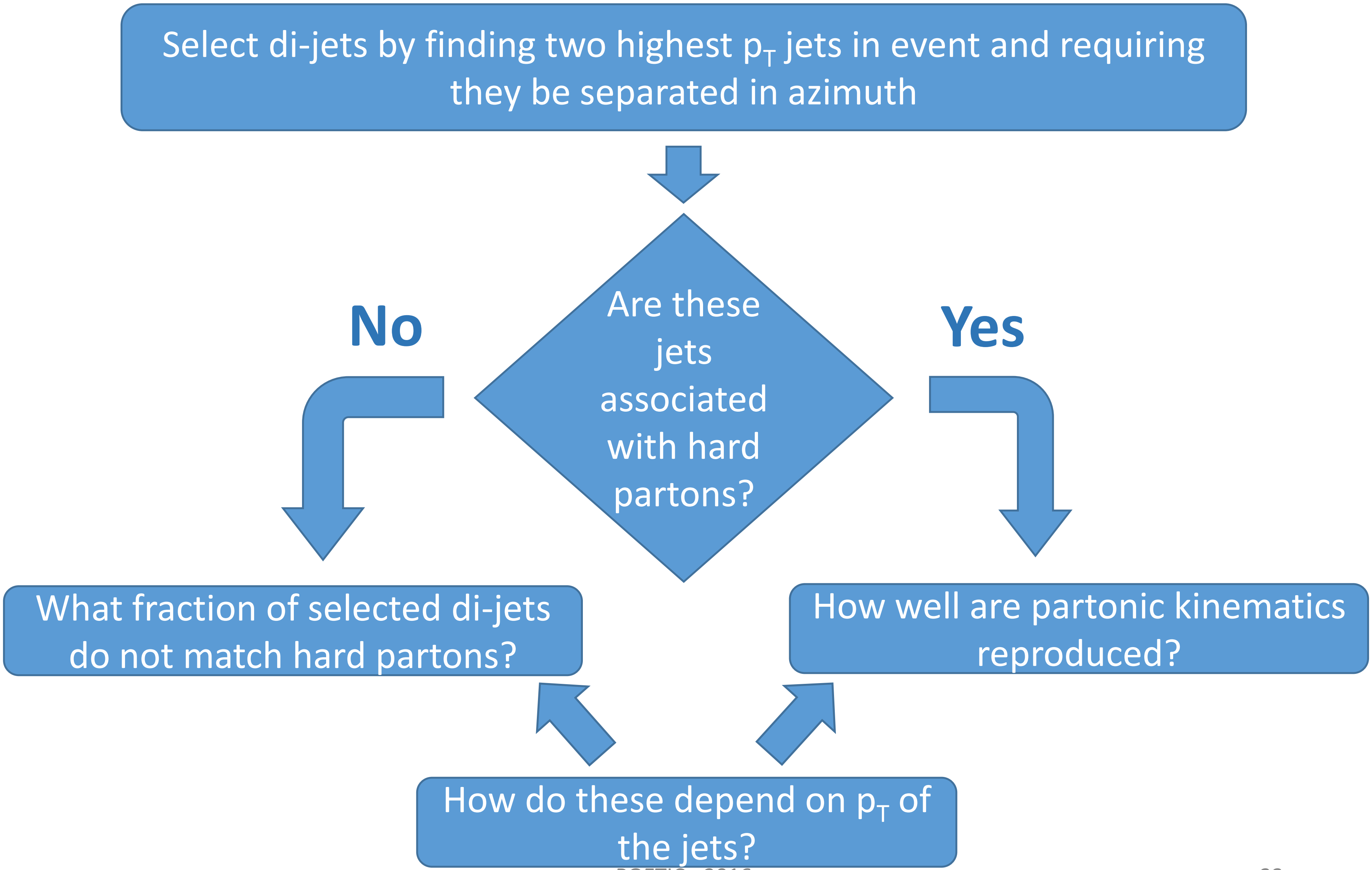
- PGF di-jet asymmetry measurements will provide alternative access to ΔG

Q^2 and x range covered by di-jet asymmetry measurements

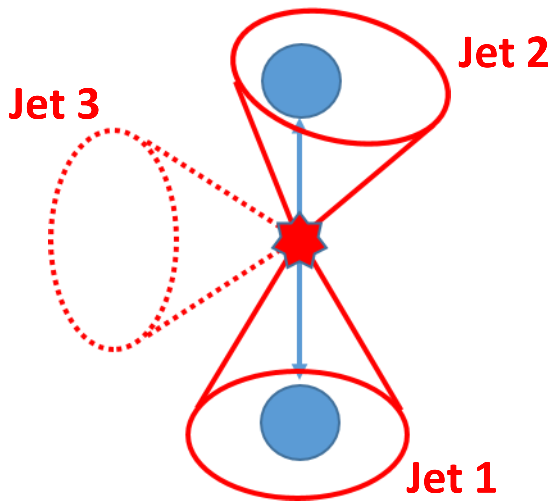
Experimentally possible to extend these measurements to $Q^2 < 1$



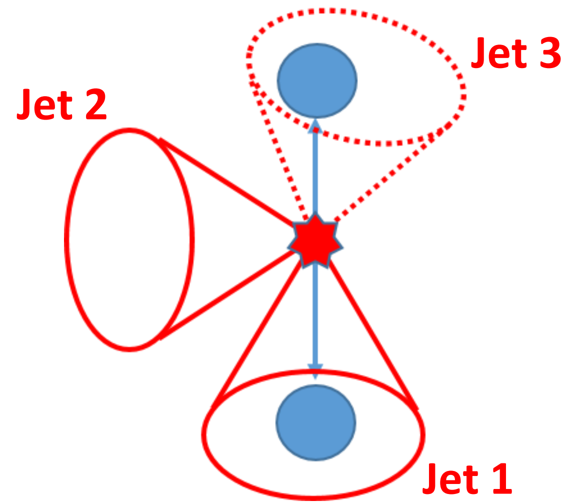
How Low Can We Go?



Matching Fractions: Q^2 = 0.01-0.1 GeV



“Matched Event”

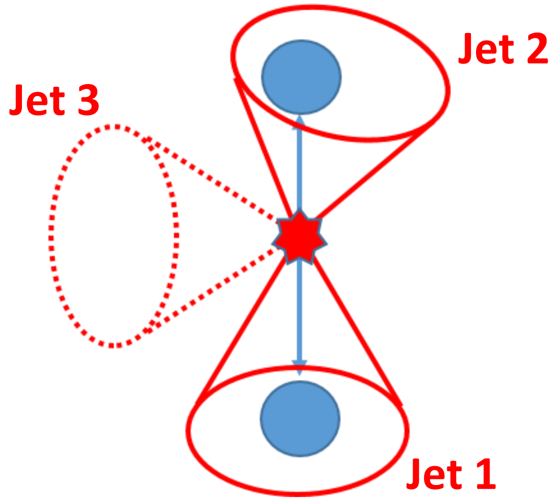


“UnMatched Event”

Jet p_T Ranges	% of PGF / Resolved Events Captured	Of Captured: % PGF / Resolved Matched
Hi Jet > 5 GeV && Lo Jet > 4 GeV	1% / <1%	87% / 83%
Hi Jet < 5 GeV || Lo Jet < 4 GeV	25% / 19%	70% / 69%

(Still require Hi Jet > 2 && Lo Jet > 1 GeV)

Matching Fractions: Q^2 = 10-100 GeV



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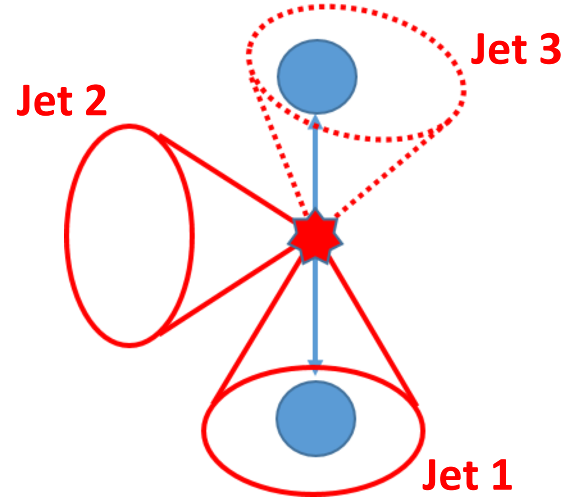
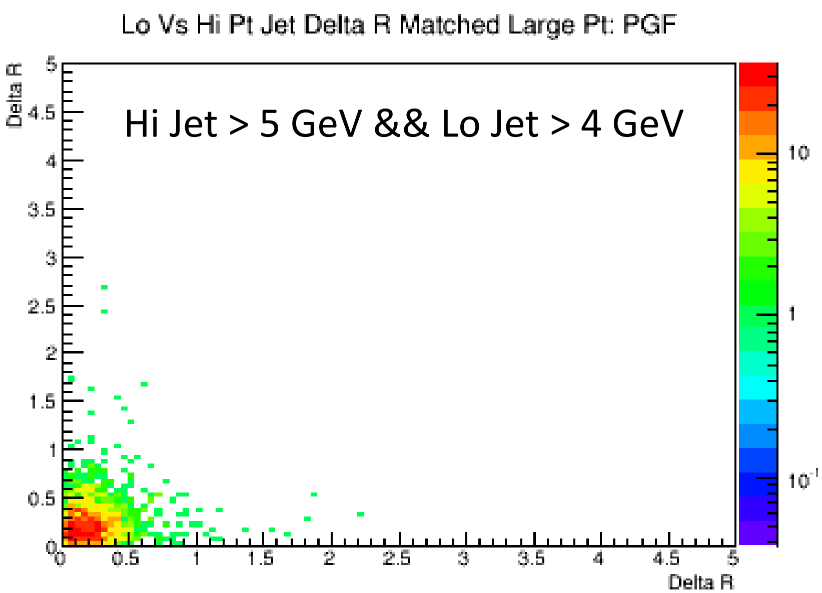
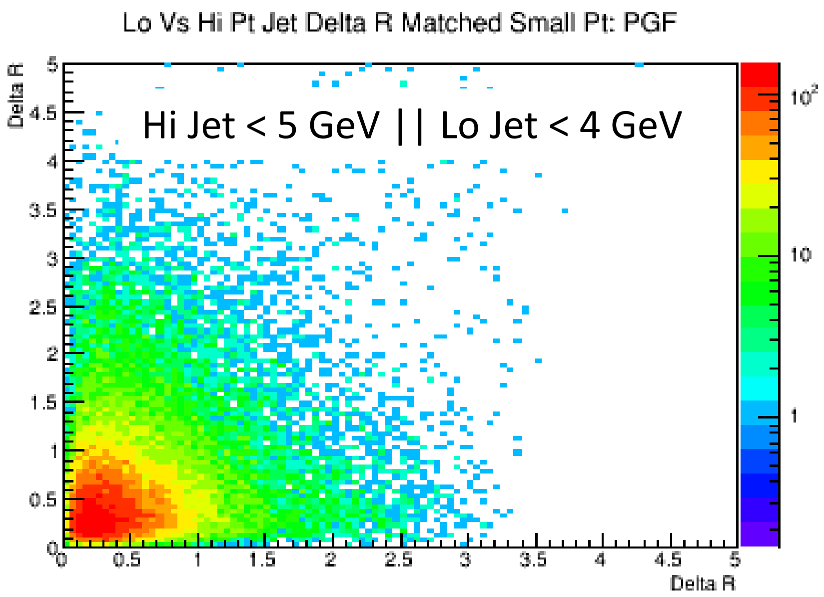


“UnMatched Event”

Jet p_T Ranges	% of PGF / Resolved Events Captured	Of Captured: % PGF / Resolved Matched
Hi Jet > 5 GeV && Lo Jet > 4 GeV	35% / 11%	91% / 91%
Hi Jet < 5 GeV || Lo Jet < 4 GeV	60% / 44%	83% / 73%

PGF ΔR: Q^2 = 0.01 – 0.1 GeV^2

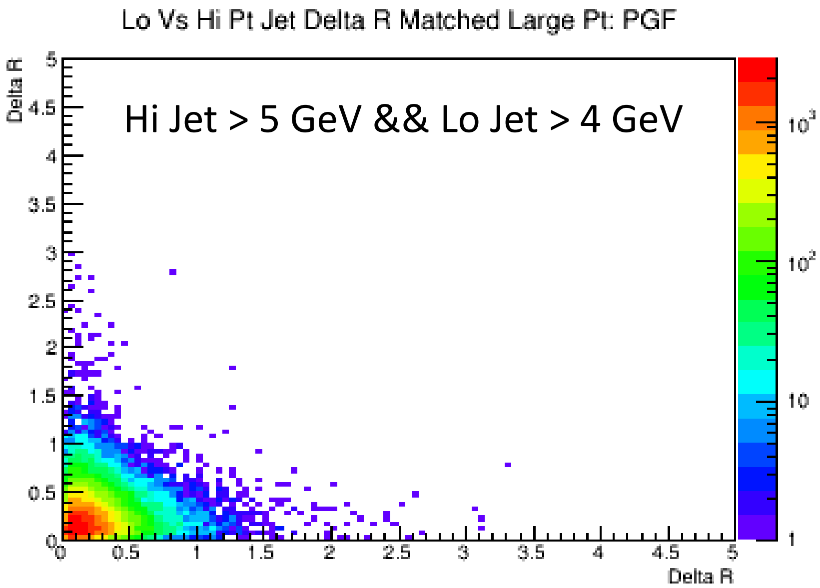


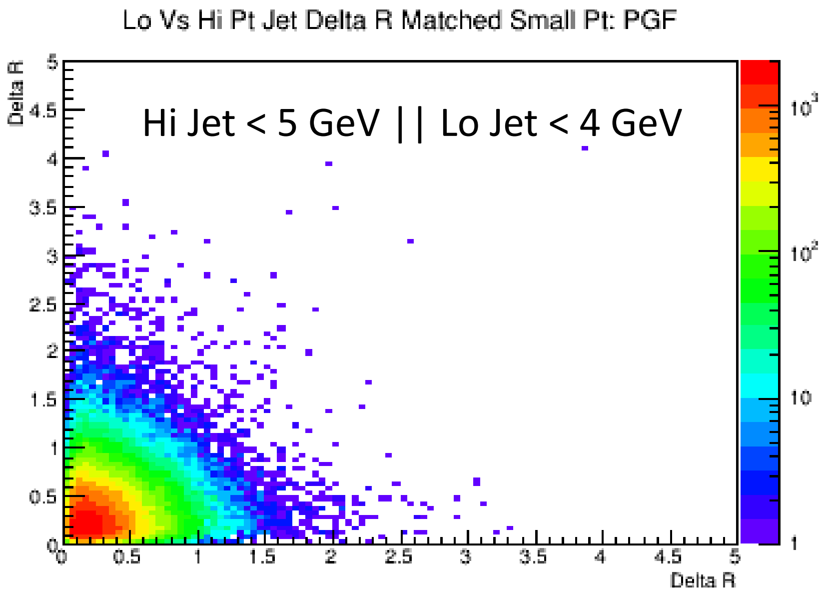


$$\Delta R = \sqrt{(y_{part} - y_{jet})^2 + (\varphi_{part} - \varphi_{jet})^2}$$

- For matched events, plot ΔR for both jets
- Do this for high and low p_T jets separately
- See that ΔR values are somewhat larger for low p_T jets – indicates poorer matching

PGF ΔR: Q^2 = 10 – 100 GeV^2

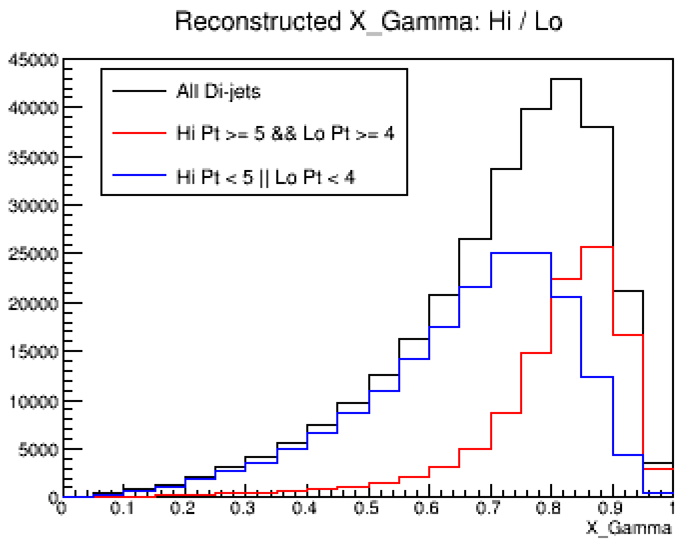


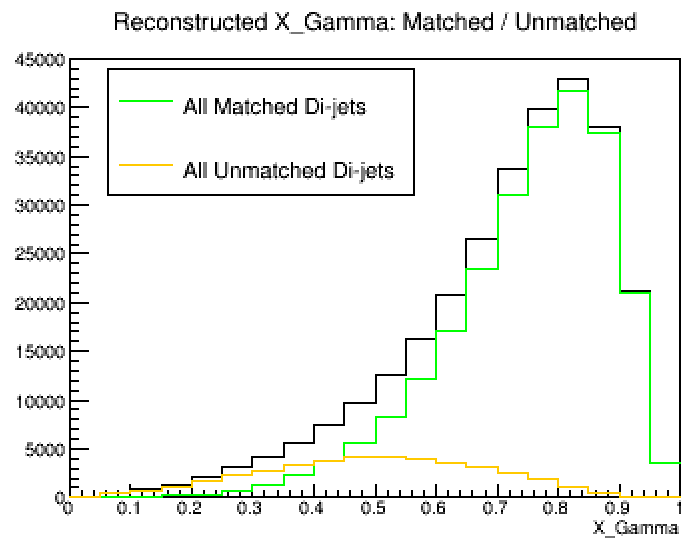


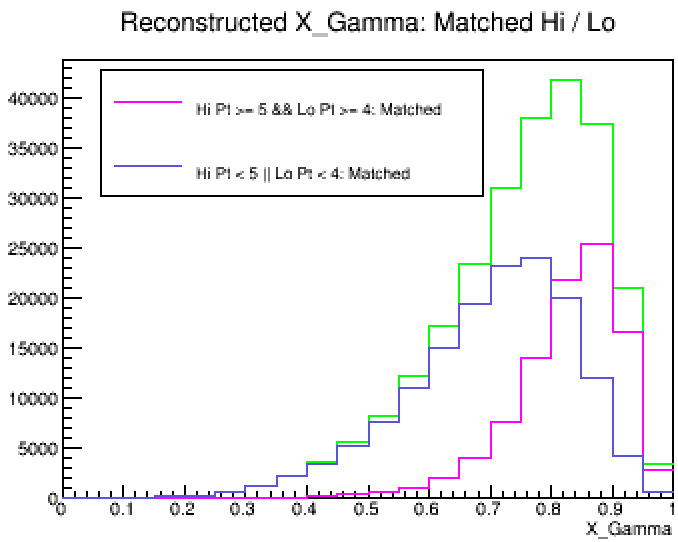
$$\Delta R = \sqrt{\left(y_{part} - y_{jet}\right)^2 + \left(\varphi_{part} - \varphi_{jet}\right)^2}$$

- The difference in ΔR behavior between low and high jet p_T is much greater at lower values of Q^2
- Similar results seen for other subprocesses

X_γ Reproduction: Q^2 = 10 – 100 GeV^2







- How does the reproduction of X_γ depend on jet p_T?
- As expected unmatched events do not reproduce X_γ well
- See that high p_T range is more peaked toward 1 even for matched events

Conclusions

- Basic jet parameters: Larger radius leads to more jets and more particles in jet, higher p_T jets have more particles but lower multiplicity. Not much dependence on jet algorithm

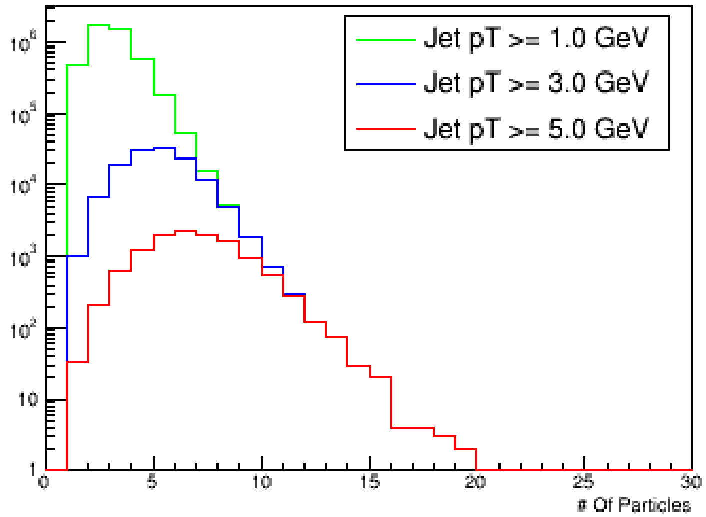
- Di-jet measurements from photon-gluon fusion subprocess will provide important cross check to gluon polarization measurements from g_1 scaling violations

- Correlation between jet and parton breaks down as jet p_T decreases meaning higher p_T jets are better for reconstructing the initial kinematics

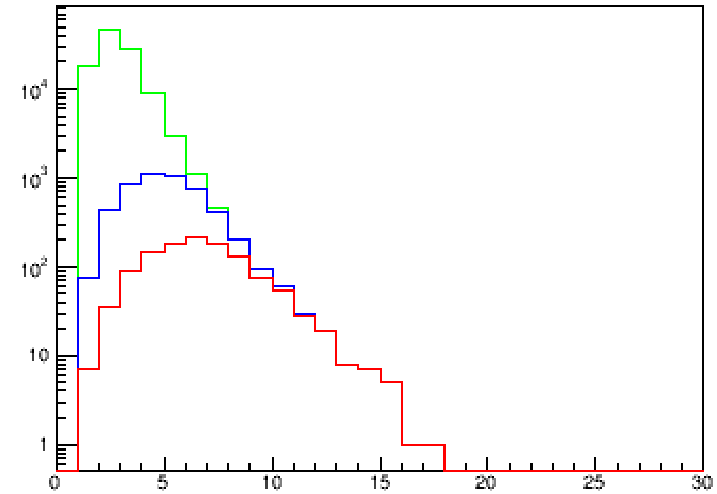
Backup

Jet Particle Mult: $Q^2 = 0.01 – 0.1\ \mathrm{GeV}^2$

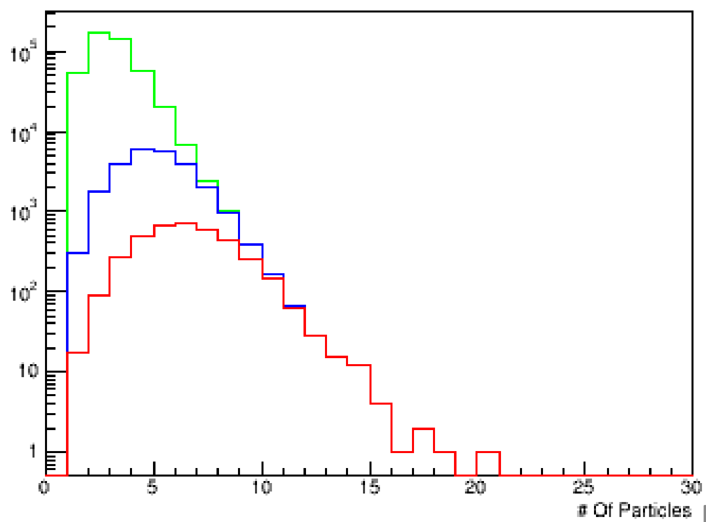
Jet Particles: Resolved



Jet Particles: QCDC



Jet Particles: PGF

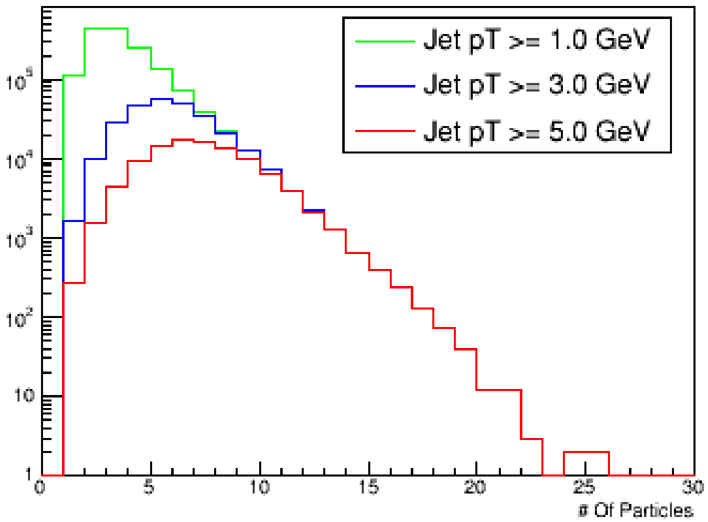


Jet Particles: L.O. DIS

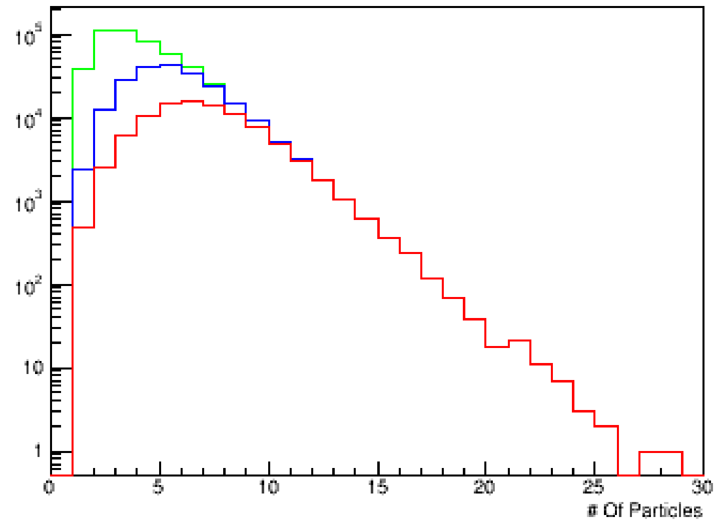
- Same as previous slide but for lower Q^2 range
- Median numbers of particles stay roughly the same as higher Q^2 case but frequency of jets with high number of particles down sharply

Jet Particle Mult: Q^2 = 10 – 100 GeV^2

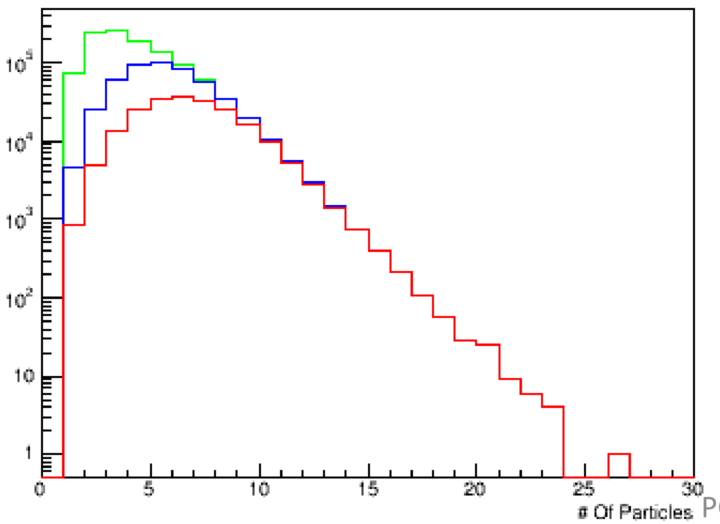
Jet Particles: Resolved



Jet Particles: QCDC



Jet Particles: PGF

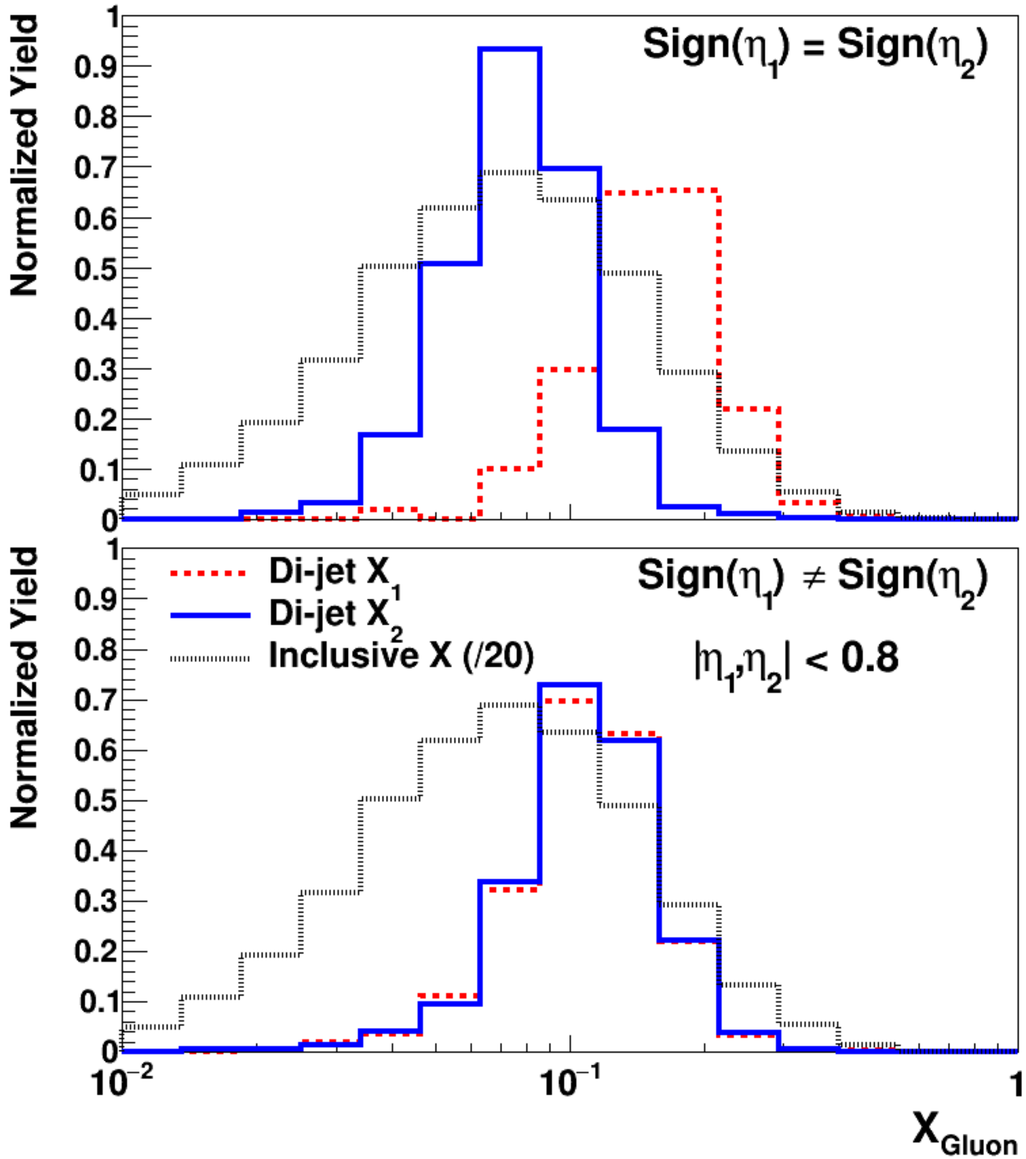


- Number of particles in a jet for 3 minimum jet p_T values
- Increase in minimum jet p_T leads to increase in average number of particles in jet
- Higher p_T jets -> more “jet like” than “single particle like”

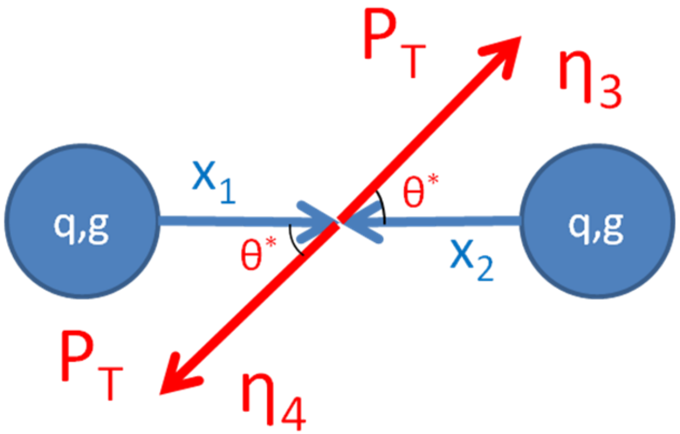
Jet Basics: Frames

- Can define several useful frames:
  - Lab: Detector-based frame
  - Hadron-Boson: Beam hadron is at rest, z-direction chosen along virtual photon momentum vector
  - Breit: Virtual photon moves in -z direction and boost such that it has zero energy. Separation into target and remnant regions
  - Center of Mass: Virtual photon and struck parton have equal and opposite momenta. Can define Feynman-x

Di-jet A_{LL} (pp)



- Coincidence measurements capture more information about hard scatter and better constrain initial kinematics



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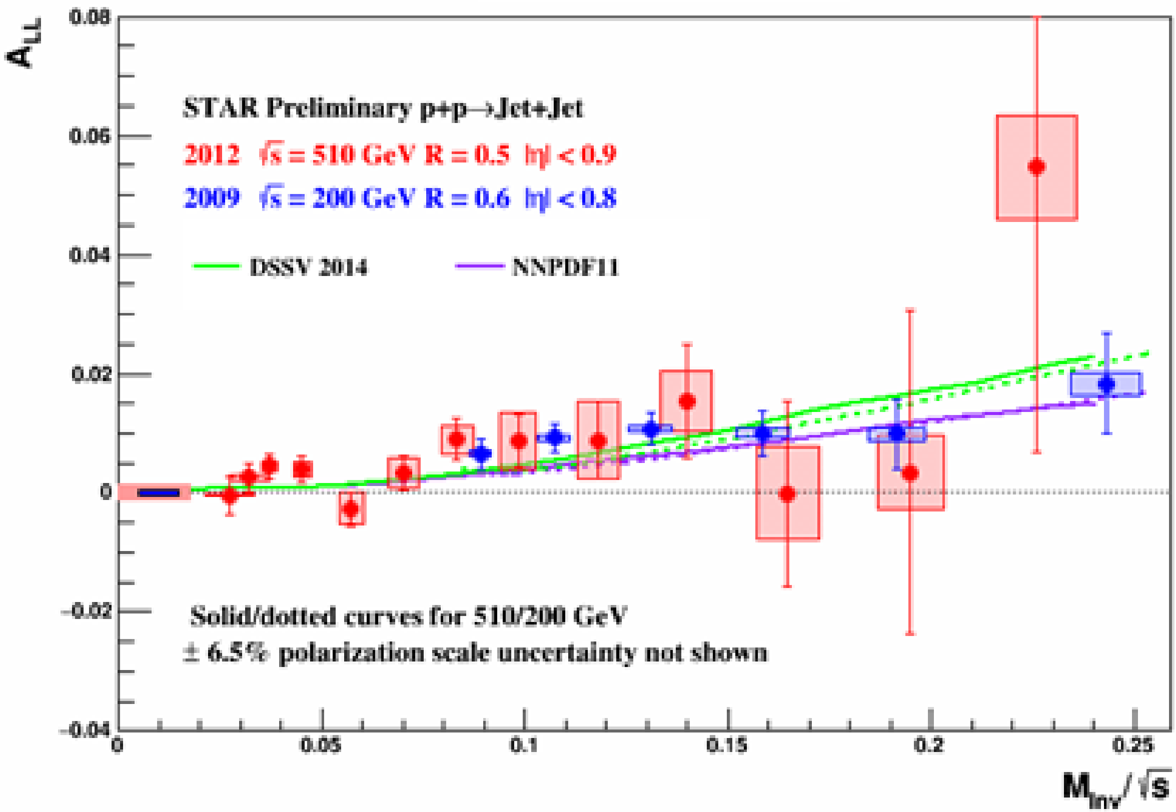
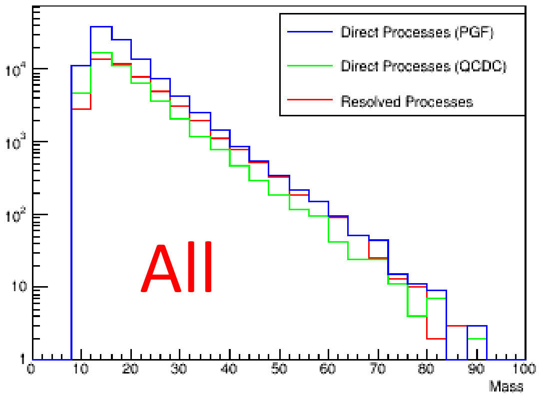


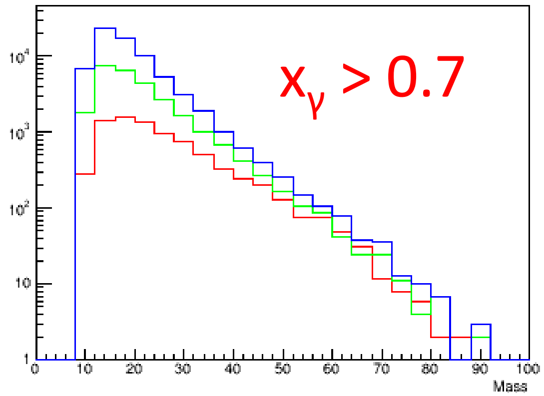
- Coincidence measurements capture more information about hard scatter and better constrain initial kinematics
- Di-jet A_{LL} plotted vs $M_{inv}/\sqrt{s}$ (~$\sqrt{x_1 x_2}$ at L.O.) for data taken at $\sqrt{s}$ = 200 and 510 GeV
- 510 GeV data extend to lower $M_{inv}/\sqrt{s}$ (lower x) where ΔG not as well constrained while 200 GeV data give better precision at mid to high $M_{inv}/\sqrt{s}$

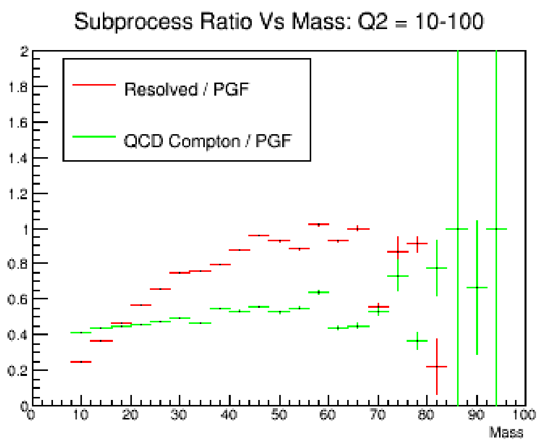
Di-jet Invariant Mass

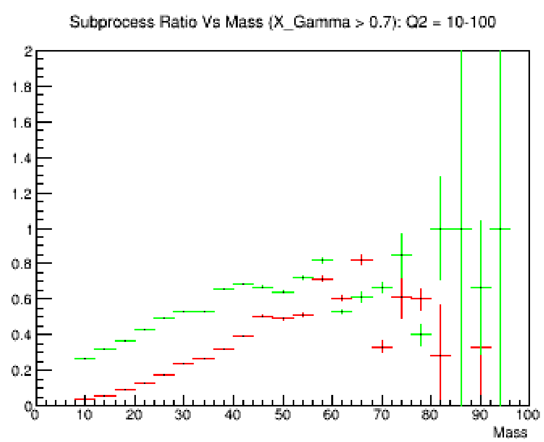
Di-jet Mass: Q^2 = 10-100



Di-jet Mass: Q^2 = 10-100



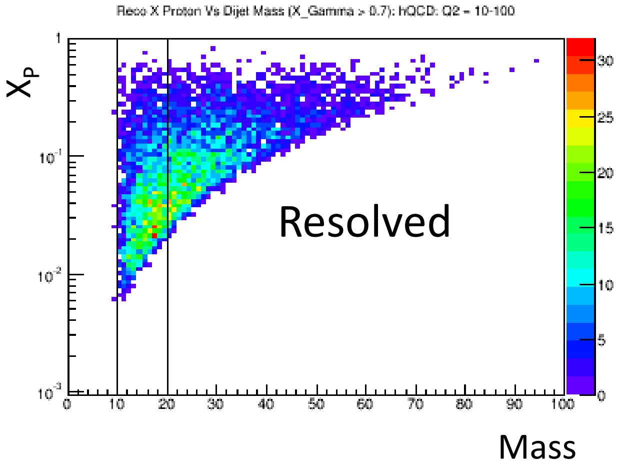


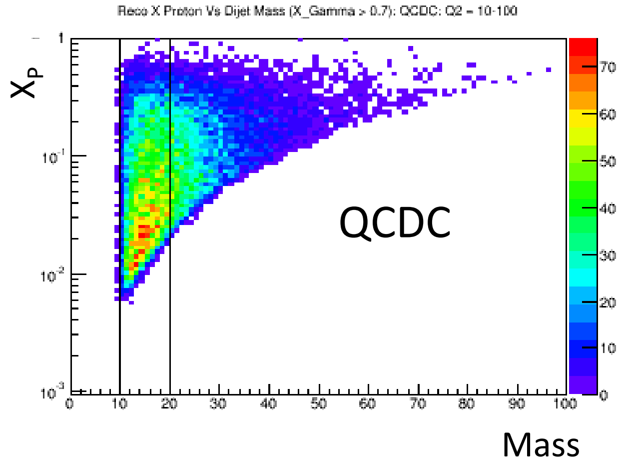


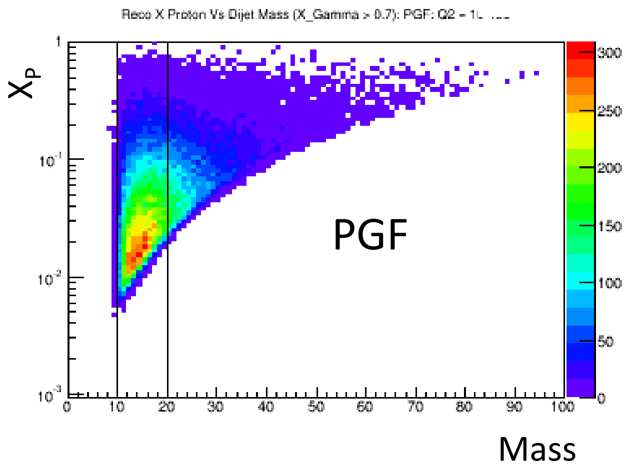
- See that the cut on X_γ significantly reduces the resolved contribution while maintaining the direct events
- Separation between resolved and direct is most prominent at high Q^2 and low di-jet invariant mass

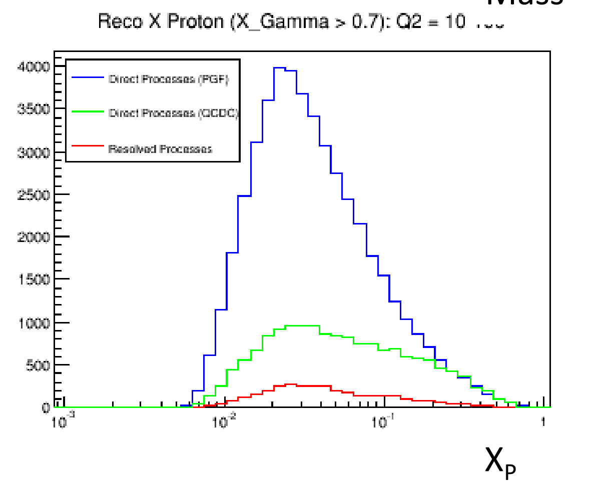
$X_{q,g}$ Vs Mass

$Q^2 = 10 - 100\ GeV/c^2$



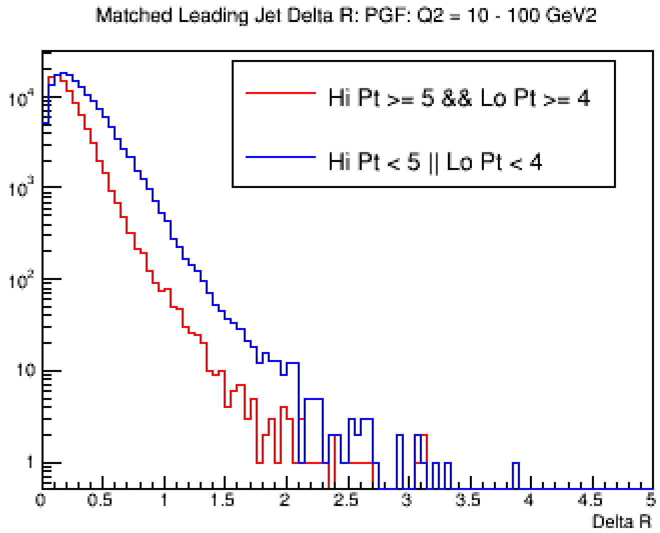


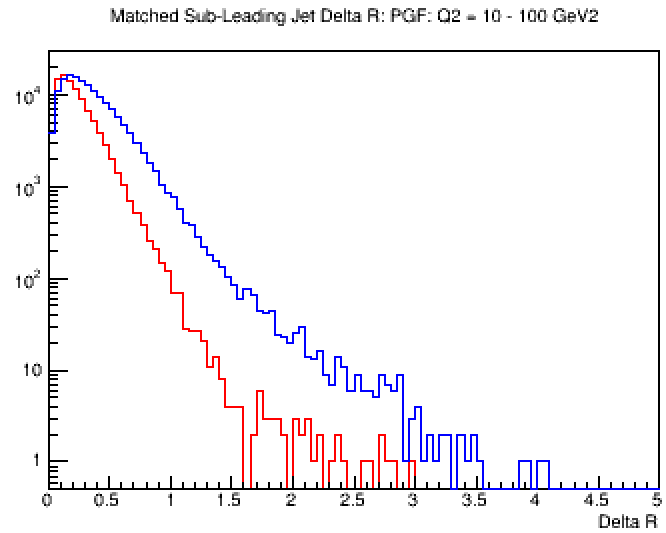


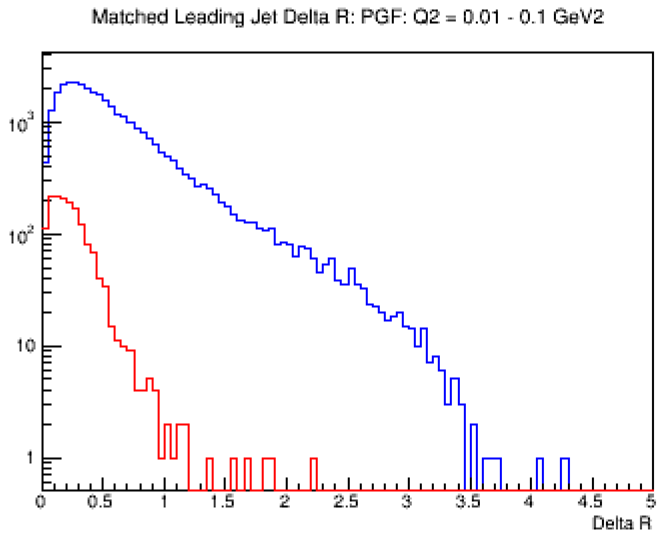


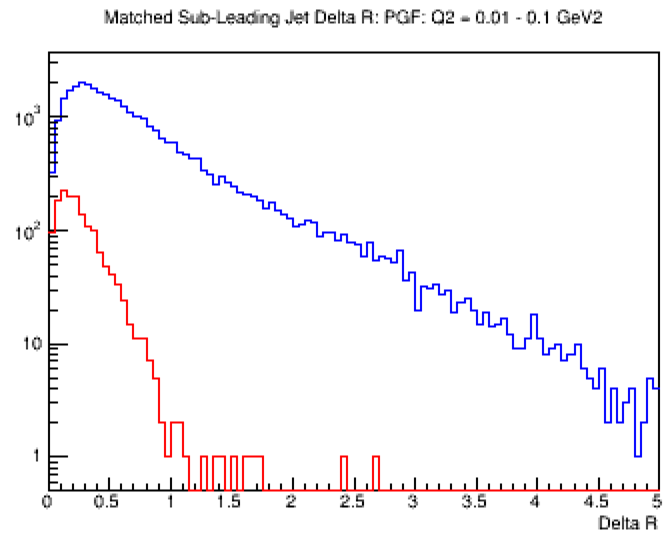
- As shown on the previous slide, accessible $X_{q,g}$ range is determined largely by beam energy
- Different di-jet mass ranges select different process fractions with lower masses containing less resolved contribution
- Selection of high mass events also cut out low $X_{q,g}$ contribution

Partonic Matching: Shape Comparison

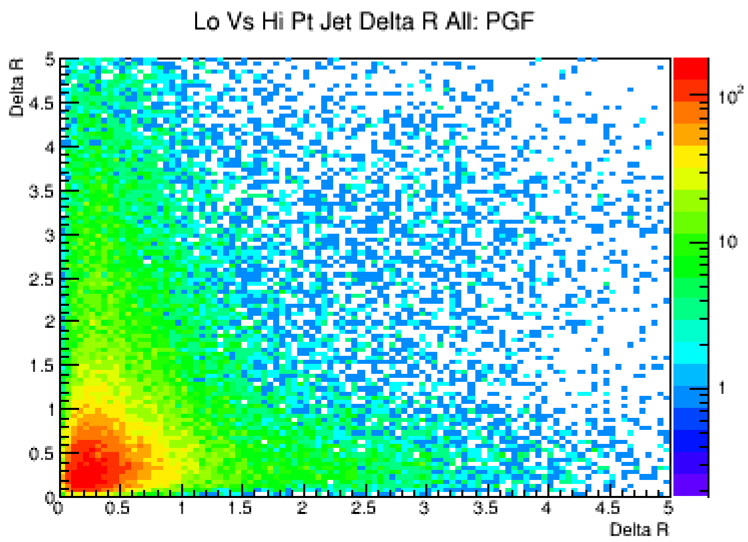


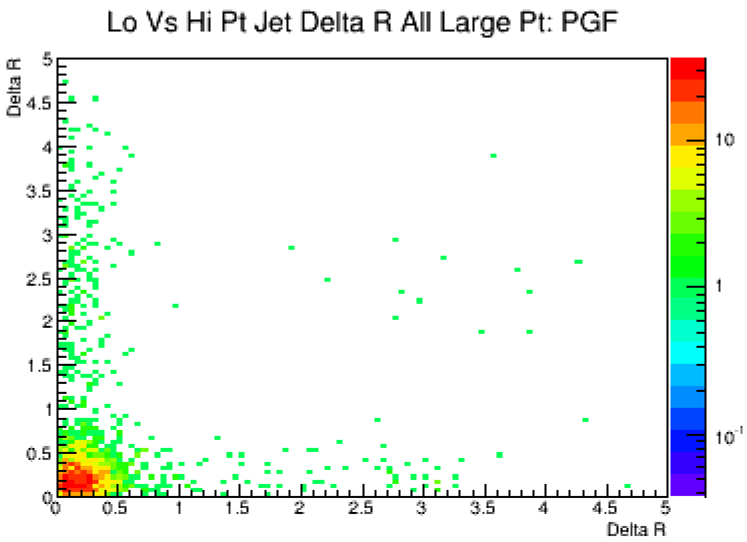


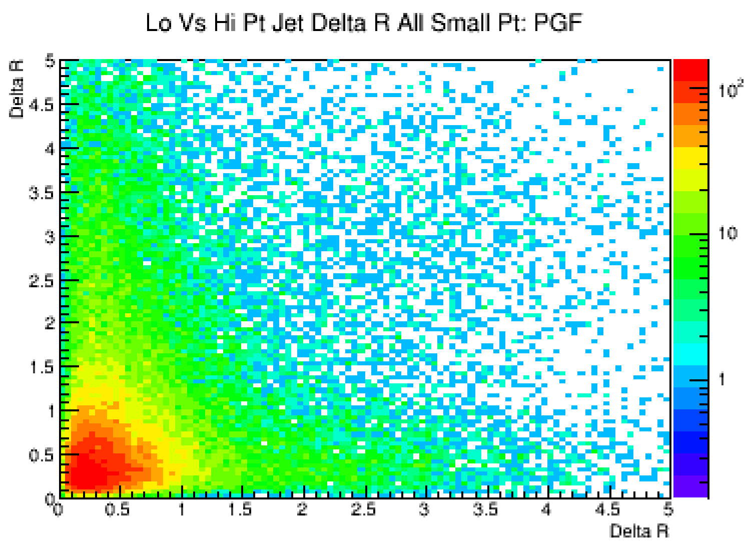




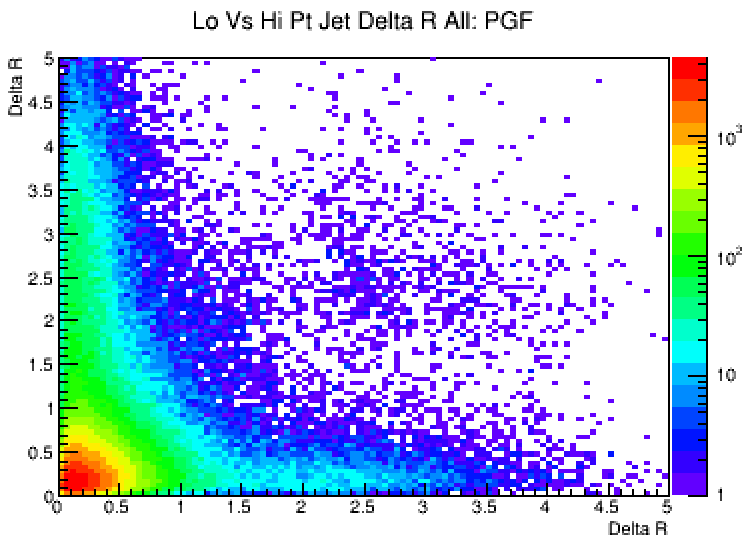
Partonic Matching: PGF Q2 = 0.01 – 0.1

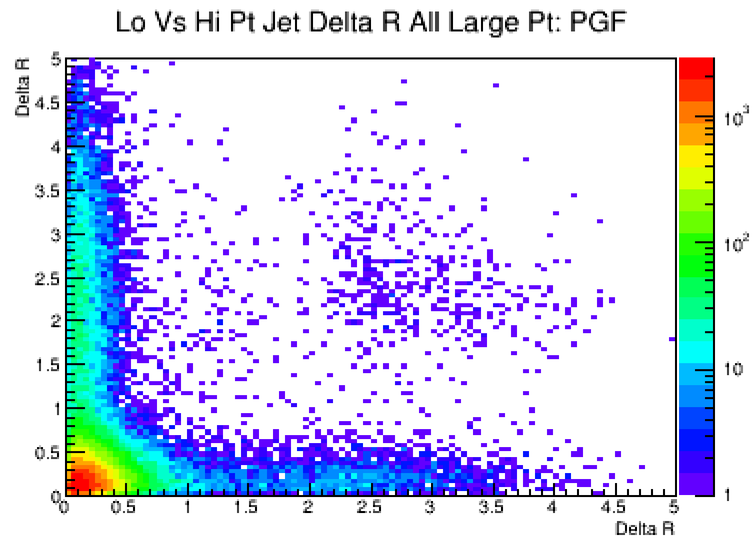


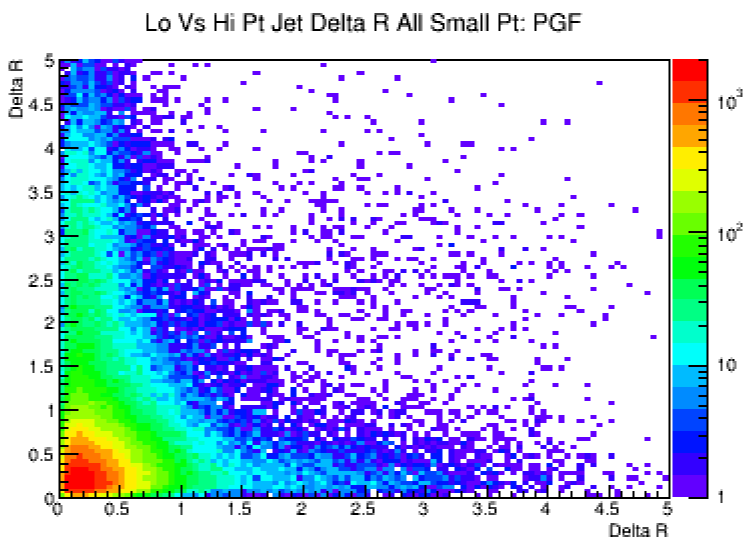




Partonic Matching: PGF Q2 = 10 - 100







X_γ Reproduction: $Q^2 = 0.01 – 0.1\ GeV^2$